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REDUCTION OF FUEL-VAPOR LOSS BY OMITTING SOME OF THE FUEL CONSTITUENTS NORMALLY LOST DURING FLIGHT

By Charles S. Stone and Walter E. Kramer

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

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MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

REDUCTION OF FUEL-VAPOR LOSS BY OMITTING SOME OF THE

FUEL CONSTITUENTS NORMALLY LOST DURING FLIGHT

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SUMMARY

An investigation was conducted to determine the effect on fuel-vapor loss during flight of omitting in the blending process some of the fuel constituents in AN-F-28, Amendment-2, fuel that are normally lost in flight. In this particular series of tests, some of the lower-boiling-point components were removed from available AN-F-28, Amendment-2, fuel by means of a fractionating column.

The results show that the fuel-vapor loss for a given set of simulated-flight conditions decreased as the percentage of fuel removed increased. Also, the altitude at which fuel-vapor loss begins (critical altitude) was found to increase as the percentage of fuel removed increased. These relations were found to depend on the initial characteristics of the original fuel sample.

The Reid vapor pressure and the A.S.T.M. 5- and 10-percent recovered points gave single-valued functions with fuel-vapor loss and critical altitude. These physical properties as indicated by data for AN-F-28, Amendment-2, fuel may be used to determine the extent of omission necessary to prevent fuel-vapor loss for a given set of flight conditions.

INTRODUCTION

Current aviation fuels contain relatively high percentages of volatile constituents, such as isopentane, in order to improve the starting and operating characteristics of the engine, especially during adverse weather conditions. Some of these highly volatile substances are added in the blending process after the base stock has been refined. Reports from the Petroleum Administrator for War have indicated that as much as 23 percent by volume of isopentane may be present in grade 100/130 fuels in order to obtain the desired physical characteristics called for in the Army-Navy specifications.

Unpublished data obtained at the NACA Cleveland laboratory indicate that the fuel lost through vaporization from the fuel tank during high-altitude flight consists mainly of the lower-boiling-point components of the original fuel. The present investigation was therefore conducted to determine the effect of omitting some of the lower-boiling-point constituents in a fuel on the fuel-vapor loss during simulated flight. This effect was determined by subjecting samples of AN-F-28, Amendment-2, fuel with up to 29.37 percent by volume of the lower-boiling-point components removed by fractional distillation to simulated flights to altitudes of 50,000 feet. Other effects that might result from the removal of the lower-boiling-point components were not investigated.

These tests were made during the latter part of 1944 and the early part of 1945 as a part of a general investigation being conducted at the NACA Cleveland laboratory at the request of the Air Technical Service Command, Army Air Forces, on means for reducing fuel-vapor loss during high-altitude flight.

APPARATUS

For this test program, the fuel samples were obtained by subjecting AN-F-28, Amendment-2, fuel to fractional distillation. The fractional-distillation apparatus used for the tests consisted of a 7-gallon, cylindrical still pot surmounted by a fractionation column and a still head. The fractionation column was a 2-inch galvanized iron pipe $7\frac{1}{2}$ feet long packed with glass helices. The helices were of glass 0.5 millimeter in diameter and were wound in chains 1/8 inch in diameter. The packed pipe was surrounded by two thin-walled iron pipes in such a manner that two annular dead-air spaces were formed about it. Three-ply corrugated asbestos insulation covered the outermost pipe. Nichrome wire was wrapped around the inner pipe to heat the column electrically when necessary. Thermocouples were placed in the column at 2-foot vertical intervals to measure the column temperatures. The still head was a modification of the one illustrated in reference 1. The system was vented through vapor traps in order to catch any vapors not condensed by the still-head condenser.

The simulated-altitude bench-test installation used is shown diagrammatically in figure 1 and photographically in figure 2. The installation is, essentially, an insulated plastic fuel tank mounted on a balance in an altitude chamber. The altitude chamber is provided with a water jacket in order to control the temperature within the chamber to 80° F ±2° F before the start of each test. The fuel tank, 10 inches in diameter and 15 inches in height, is vented directly to the altitude chamber through a valve by means of a 3-foot length of neoprene tubing 3/4 inch in inside diameter. The pressure within the fuel tank is manually controlled by air-bleed valves in conjunction with a vacuum pump in order to simulate a predetermined flight path. The apparatus used to indicate and control the pressure altitude is essentially the same as that described in reference 2. The fuel losses are determined by means of the balance. Five thermocouples, used to measure the fuel and vapor temperatures during the tests, were placed within the fuel tank and were spaced at $3\frac{1}{4}$-inch intervals starting 1/2 inch above the bottom midway between the center and the outer wall of the fuel tank.

A hot-water heat exchanger used as a fuel-temperature regulator heated the fuel to the desired initial temperature before it was run into the fuel tank. A flexible hose leading from the heat exchanger through an access door in the altitude chamber permitted the fuel to be transferred to the fuel tank at the end of the heating process.

An A.S.T.M. gasoline-distillation apparatus, Reid vapor-pressure bombs, and an analytical-type Westphal balance were used to obtain distillation curves, vapor pressures, and specific gravities, respectively, of the various fuel samples withdrawn.

TEST PROCEDURE

Preparation of Fuel Samples

For each test, a fuel sample was prepared by introducing approximately 26 pounds of AN-F-28, Amendment-2, fuel into the still pot of the fractionating column. The fuel in the still pot was then heated and the column, refluxing continuously, was allowed to come to equilibrium at 78° F to 80° F over a period of 24 hours. The distillate was then removed at a rate of 80 to 90 drops per minute until the desired amount had been obtained. After the distillate had been removed, the heaters were shut off and the residual fuel was allowed to cool over a period of 12 hours before it was drained. The weights of the residual fuel and the distillate were recorded and samples of each were removed for analysis.

Simulated-Flight Tests

In each simulated-flight test conducted, approximately 15 pounds of each fuel sample was used. The fuel was first heated to approximately 115° F in the fuel-temperature regulator and was then transferred to the fuel tank in the altitude chamber. The fuel entered the fuel tank at a temperature of approximately 112° F and was then allowed to cool to 110° F ±0.5° F in the fuel tank before the simulated-flight test was started. All vents and openings of the fuel tank were closed while the fuel was being heated in the temperature regulator and while the fuel was cooling in the fuel tank.

The simulated flights to induce fuel-vapor loss consisted in a climb at 2000 feet per minute to an altitude of 50,000 feet with this altitude maintained for a total test duration of 85 minutes. The fuel within the tank was not mechanically agitated during the test. Fuel and vapor temperatures and the weight of fuel lost by vaporization were recorded at intervals during the tests.

A 1-quart sample of the fuel was taken before the fuel was heated, and before the start and after the completion of each simulated-flight test, in order to obtain Reid vapor pressures, specific gravities, and A.S.T.M. distillation curves.

PRESENTATION OF THE RESULTS

During the fractionation process for obtaining the fuel samples, small losses of fuel due to column leakage and drainage were unavoidable. Inasmuch as leakage, drainage, and filling losses could not be determined, the data cannot be presented on the basis of percentage removed by fractionation. Instead the data are presented as a range between the minimum and maximum limits of the amount removed by fractionation (calculated on the basis of (1) the distillate recovered and (2) the amount removed from the original fuel). Although the exact amount removed by fractionation was not known, it falls somewhere between these two limits and therefore presentation of the data as ranges reveals trends and gives approximate values for comparison and analysis.

Inasmuch as the tests were conducted with three barrels of AN-F-28, Amendment-2, fuel, which were not necessarily from the same original source of supply, some differences in the physical properties of the fuel are to be expected because the Army-Navy specification for this grade of fuel allows rather wide variations. Although a number of tests was conducted and a large quantity of data was accumulated, it was found advisable to omit some of the data points on a few of the curves for the sake of clarity.

Physical Properties of the Fuel

The A.S.T.M. distillation curves of a representative group of fuel samples and of the distillate removed are shown in figure 3. The effect of removing increasingly greater quantities of the lower-boiling-point components of the fuel by fractional distillation was merely to increase the distillation temperature in the lower portion of the curve whereas the upper portion of the curve remained relatively unaffected. The fact that the A.S.T.M. distillation curve of the distillate (that portion of the fuel removed by fractionation) is very nearly a horizontal line indicates the presence of a large quantity of a single compound, probably isopentane, the boiling point of which is 82.2° F (reference 3, p. 1).

The effect of the removal of some of the lower-boiling-point components on several of the physical properties of the fuel is brought out in figure 4 where the Reid vapor pressure, the specific gravity, and the A.S.T.M. distillation temperatures are plotted as functions of the percentage of fuel removed by fractionation. Figure 4 shows that the Reid vapor pressure decreases, whereas the specific gravity and the A.S.T.M. temperatures increase, as the amount of fuel removed by fractionation increases. The presence of two separate curves for specific gravity is, as was explained previously, the result of the use of a different barrel of AN-F-28, Amendment-2, fuel for each series of tests. The use of the different barrels of fuel apparently did not seriously affect the correlation between the percentage of fuel removed and either the Reid vapor pressures or the A.S.T.M. distillation temperatures.

Simulated-Flight Tests

The results of the simulated-flight tests on the several fractionated fuels are presented in figure 5 where the fuel-vapor loss, the average fuel temperature, and the average temperature of the vapor above the fuel in the tank are plotted as functions of flight time. Most of the fuel-vapor loss takes place during the climb period (in the first 25 min of the flight) with only a small increase in the loss during the constant-altitude portion of the flight. After the end of the climb, the fuel apparently becomes stabilized at the 50,000-foot altitude, after a short (5 to 10 min) period, and the loss from that point on seems to be almost linear at a rate of approximately 1-percent loss per hour for the rest of the test. All the loss curves have the same general shape. Regardless of the quantity of lower-boiling-point components removed from the fuel, the rate of loss with time is practically the same after the "critical" altitude (the theoretical altitude at which fuel-vapor loss begins) has been reached.

The curves of average fuel temperatures during the simulated flight appear to be the inverse of the fuel-vapor-loss curves; the greatest change in temperature takes place during the climb and at a constant rate with time. The greatest temperature change takes place with the fuel undergoing the greatest vapor loss (the fuel sample having none of its lower-boiling-point components removed). The fuel temperature levels off at the end of the climb and remains very nearly constant throughout the constant-altitude portion of the simulated flight. As with the fuel-vapor-loss curves, all the fuel-temperature curves have the same general shape, the rate of change of temperature during simulated flight being practically the same, regardless of the quantity of fuel fractionated, after the critical altitude has been reached.

The curves showing the average temperature of the vapor above the fuel in the fuel tank (fig. 5) reveal general trends that may be of interest. As the simulated flight progresses, the vapor temperature rapidly rises to approach the average fuel temperature and then the curve assumes the same form as the average fuel-temperature curve but with slightly lower values.

ANALYSIS OF THE RESULTS

The data obtained during the climb period of the simulated flight, which show the fuel-vapor loss as a function of altitude and of the change in fuel temperature, are plotted in figure 6. Each curve of fuel-vapor loss with altitude shows a negligible loss up to an approximate critical altitude from which point the fuel-vapor loss increases linearly with altitude. The small transition section preceding the linear portion of the curve may have been caused by the presence of air either in solution with the fuel or above the fuel, which upon being removed carried with it some fuel vapor. The critical altitude can be determined by extending the linear portion of the curve to the point of zero loss.

A unique characteristic of the series of curves of fuel-vapor loss with altitude is the fact that, after the critical altitude has been reached, the weight rate of fuel-vapor loss with altitude is the same regardless of the quantity of lower-boiling-point components removed from the fuel up to the removal of approximately 15 percent. The only effect, then, of removing increased amounts of the lower-boiling-point components of the fuel is to raise the boiling altitude of the fuel, but once the boiling altitude has been exceeded the rate of fuel-vapor loss with altitude is constant.

The series of curves of fuel-vapor loss with fuel-temperature drop is presented in figure 6 to show the effect of the fuel vaporization on the temperature of the fuel remaining in the fuel tank. The change in fuel temperature during the simulated climb for each fuel sample varied linearly with the loss except for a small portion of the curve at low losses. This transition period may also have been caused by the presence of dissolved air in the fuel which, upon coming out of solution, carried with it some fuel vapor and thereby decreased the temperature of the fuel. Although the rate of change of fuel temperature with fuel-vapor loss is approximately the same for all the fuel samples, the curves are slightly displaced from each other with the result that for a given fuel-vapor loss the fuel with the greatest quantity of lower-boiling-point components removed by fractionation undergoes the greatest drop in fuel temperature.

The A.S.T.M. distillation curves of some of the fuel samples before and after simulated flight are shown in figure 7. Although the spread in temperatures in the lower portion of the distillation curve is still present after the fuel samples have been subjected to simulated flight, the temperature spread is less than that of the samples before the simulated flight.

The effect of the removal of the lower-boiling-point components on the fuel-vapor loss and the critical altitude of the fuel is shown in figure 8. Although the loss decreases by appreciable amounts, the amount of decrease is different for each barrel of fuel from different batches. These differences can be expected because the Army-Navy specification for AN-F-28, Amendment-2, fuel allows a variation to exist in those physical properties which are important with respect to fuel-vapor loss; for example, Reid vapor pressure, A.S.T.M. distillation temperatures, and specific gravity.

Although the amount of fuel removed by fractionation could not be accurately determined and is presented as a range between two limits, some of the physical properties of the fuel may be used to indicate the effect of the removal of the lower-boiling-point components of the fuel on fuel-vapor loss. (See fig. 9(a)). The use of three barrels of AN-F-28, Amendment-2, fuel gives three separate and distinct linear curves of fuel-vapor loss plotted against specific gravity but no such distinction is shown when fuel-vapor loss is plotted against Reid vapor pressure or A.S.T.M. distillation temperatures at initial boiling point, 5-percent point, or 10-percent point.

The curve of fuel-vapor loss for the simulated-flight tests plotted against Reid vapor pressure is approximately linear for Reid vapor pressures between 3.5 and 6.5 pounds per square inch but the loss drops more rapidly when the Reid vapor pressure is decreased below approximately 3.5 pounds per square inch.

The A.S.T.M. distillation temperatures at initial boiling point, 5-percent point, or 10-percent point give linear curves when they are plotted against fuel-vapor loss. The extreme spread in the points on the A.S.T.M. initial-boiling-point curve seems to eliminate its possible use as a measure of the loss to be expected during this particular simulated flight, but the 5- or 10-percent recovered curves are reasonable.

The initial specific gravity of the fuel is eliminated as an indication of the fuel-vapor loss to be expected due to the variation in the three barrels of fuel but, as has been shown in reference 4, the change in the specific gravity of the fuel can be used to indicate the fuel-vapor loss that has occurred.

Because of the linearity of the curve showing fuel-temperature drop plotted against fuel-vapor loss (fig. 6), it is possible that the fuel-temperature drop may also be a good indication of the loss that has occurred during the simulated flight. If the physical properties of the fuel samples are to be used to predict the fuel-vapor loss during a simulated climb to a 50,000-foot altitude, then either the Reid vapor pressure or the A.S.T.M. 5- or 10-percent recovered curves should be used.

Much useful information was obtained by considering the variation of fuel-vapor loss with the changes in the physical properties of the fuel samples, but the effect on the critical altitude of decreasing the amount of lower-boiling-point components in the fuel is of more practical value. Figure 9(b) shows the critical altitude of the fuel samples (with the fuel at a temperature of 110° F at the start of the simulated flight) plotted against Reid vapor pressure, specific gravity, and A. S. T. M. distillation temperatures. As has been previously indicated, although the critical altitude varies linearly with the specific gravity, the use of different samples of AN-F-28, Amendment-2, fuel gives separate and distinct curves. Inasmuch as the critical altitude approximates the actual boiling altitude of the fuel, the critical altitude varies almost exponentially with the Reid vapor pressure. If a flight is desired to an altitude of 40,000 feet (with the fuel at an initial temperature of 110° F) without appreciable fuel-vapor loss, it can be seen from figure 9(b) that the fuel must have a Reid vapor pressure of approximately 2.8 pounds per square inch. The critical altitude also varies linearly with the A. S. T. M. distillation temperatures with considerably more scatter of the data in the initial boiling-point temperature than either the 5- or 10-percent recovery curves.

DISCUSSION

In general, the reduction in fuel-vapor loss due to the omission of increased amounts of the lower-boiling-point components of the fuel is caused by the successive reductions in the vapor pressure of the fuel. The decreased vapor pressure of the fuel increases only the critical altitude of the fuel and apparently does not affect the rate of loss with altitude after the critical altitude has been reached (that is, within the limits of these tests). Omission of the lower-boiling-point components of the fuel increases the specific gravity because some of the lighter portions of the fuel are omitted. Differences in the initial specific gravity, within the limits of these tests, apparently do not affect the fuel-vapor loss during simulated flight. Volatility of the fuel or its tendency to vaporize due to decreased atmospheric pressure, increased fuel temperature, or both can be indicated either by the Reid vapor pressure or the A. S. T. M. 5- and 10-percent distillation temperatures.

It is emphasized that in practice the consideration of the reduction of fuel-vapor loss by omission of some of the lower-boiling-point components should be influenced by factors such as:

(1) Possible fuel-production curtailment
(2) Engine starting
(3) Engine performance with less volatile fuel
(4) Climatic conditions under which the fuel will be used
(5) Operating altitudes and ranges

All these factors should be investigated although analysis shows that some effects of the omission may not be serious.

Under those operating conditions where fuel-vapor loss occurs, engine starting, cruise operation, or the explosibility of the mixture in the fuel tank may not necessarily be affected. Starting may not be made more difficult after the first flight because the fuel in the fuel lines between the fuel tank and the carburetor nozzle, which would be the fuel used in starting, is weathered fuel that has been subjected to altitude conditions. Cruise operation of the aircraft may not be affected, inasmuch as the fuel used during this period of flight is fuel that has already been weathered. The decrease in fuel-vapor pressure due to omission may increase the danger of explosion when the fuel tank is penetrated by gunfire; however, this hazard may be equally dangerous with current fuels after some of the lower-boiling-point components of the fuel have been lost through vaporization.

Decreased fuel-vapor pressure can be beneficial to the operation of the aircraft. The tendency of a fuel system toward vapor locking is markedly decreased as the fuel-vapor pressure is decreased. If the fuel-vapor pressure is decreased sufficiently to raise the critical altitude of the fuel above the altitude at which the aircraft is likely to operate, additional fuel losses due to boiling over (which may in some cases be large) are also eliminated.

SUMMARY OF RESULTS

When AN-F-28, Amendment-2, fuel with various amounts of the lower-boiling-point components removed was subjected to simulated flight in a bench-test installation, the following results were obtained:

1. Increased removal of the lower-boiling-point components decreased the fuel-vapor loss and increased the critical altitude by amounts which varied with the physical characteristics of the fuel sample.

2. The Reid vapor pressure and the A. S. T. M. 5- and 10-percent recovered points gave single-valued functions with fuel-vapor loss and critical altitude. These physical properties of the fuel may be used to determine the amount of omission necessary to prevent fuel-vapor loss for a given set of flight conditions.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 27, 1945.

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4. Stone, Charles S., and Kramer, Walter E.: Fuel-Vaporization Loss as Determined by the Change in the Specific Gravity of the Fuel in an Aircraft Fuel Tank. NACA RB No. E5E19, 1945.

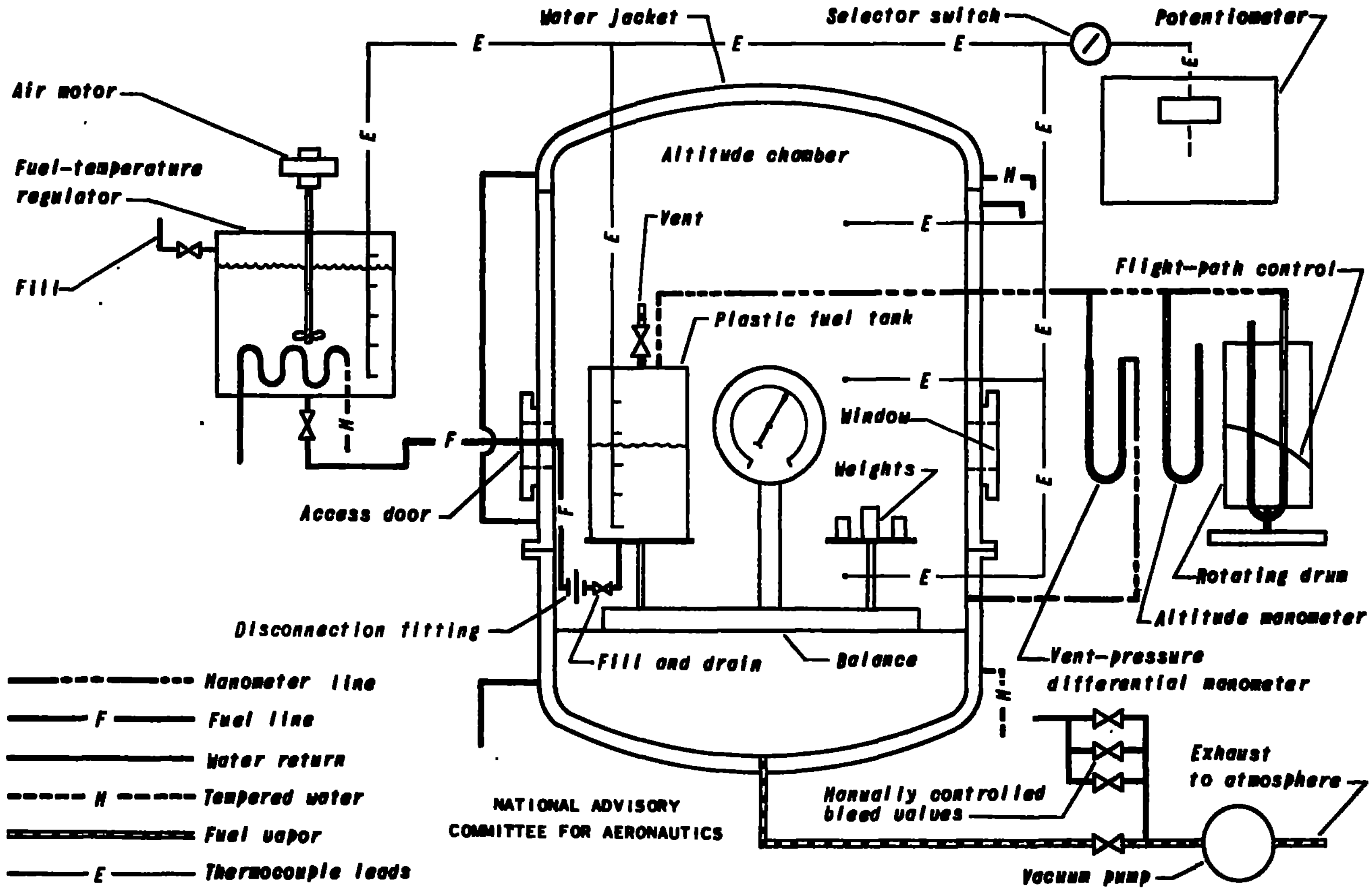
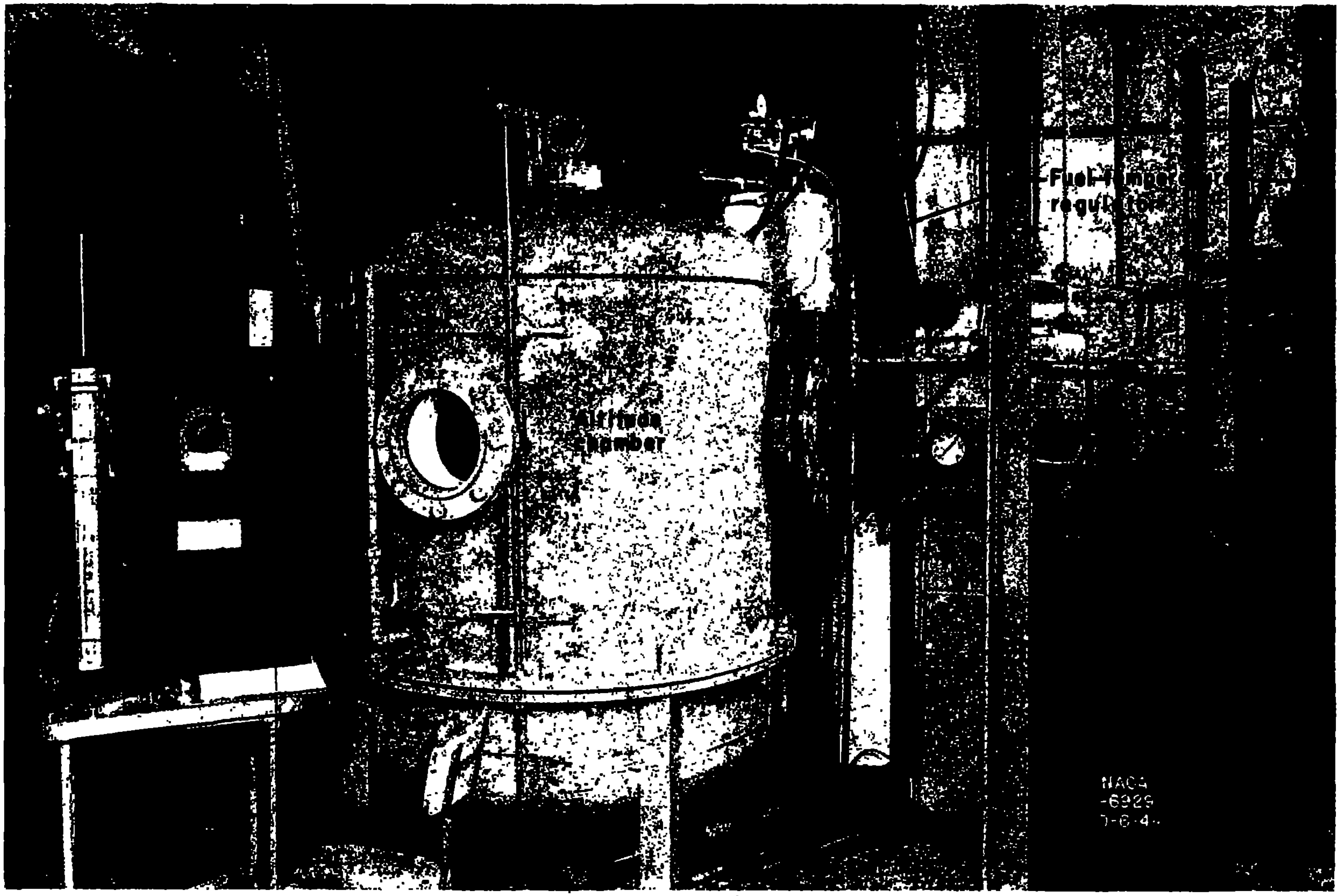
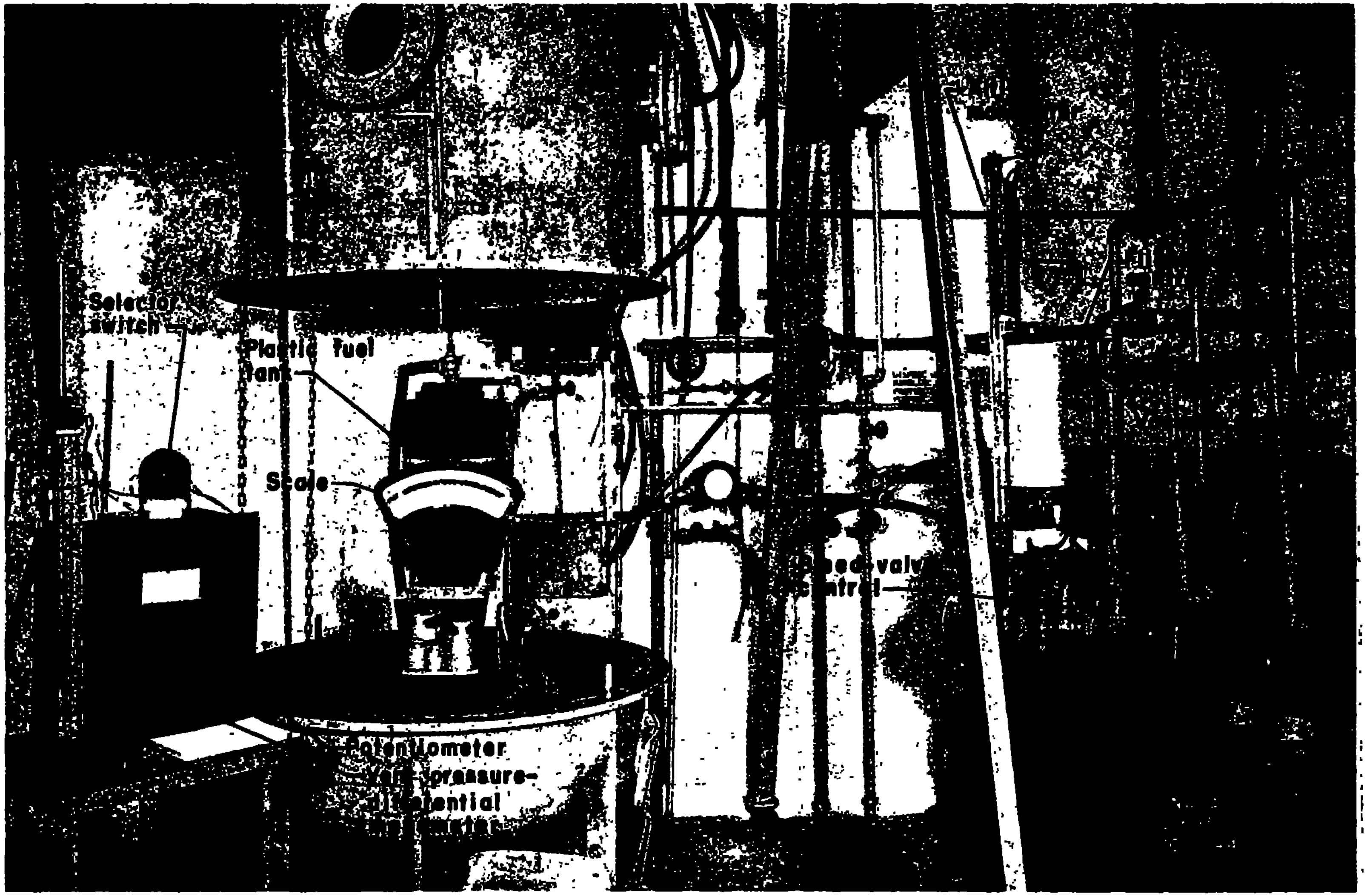


Figure 1. - Diagrammatic sketch of simulated-altitude bench-test installation.



(a) Altitude chamber closed.

Figure 2. - Simulated-altitude bench-test installation.



(b) Altitude chamber open.

Figure 2. - Concluded. Simulated-altitude bench-test installation.

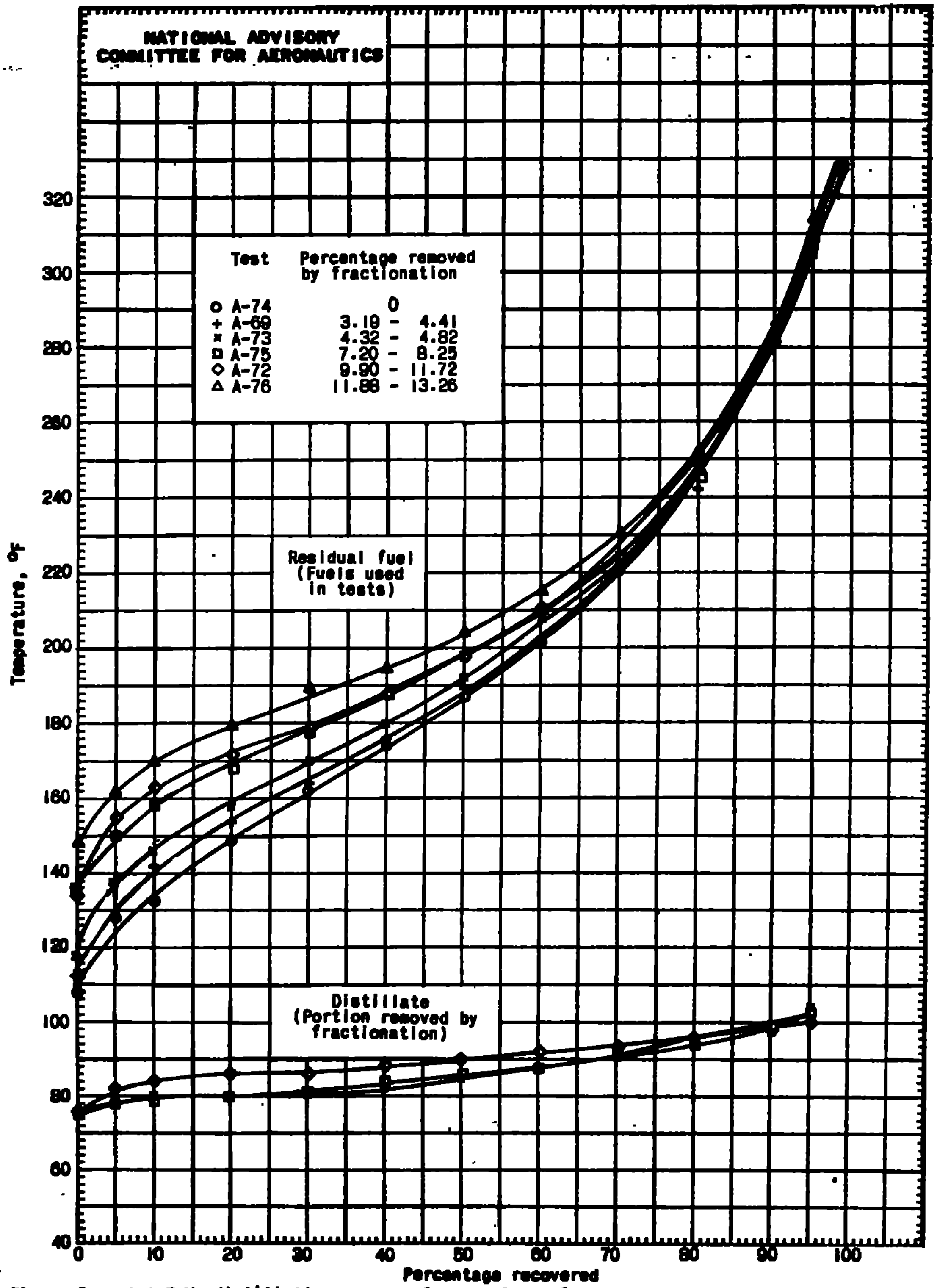


Figure 3. - A.S.T.M. distillation curves of some of the fuel samples used in the tests and of the portions removed by fractionation.

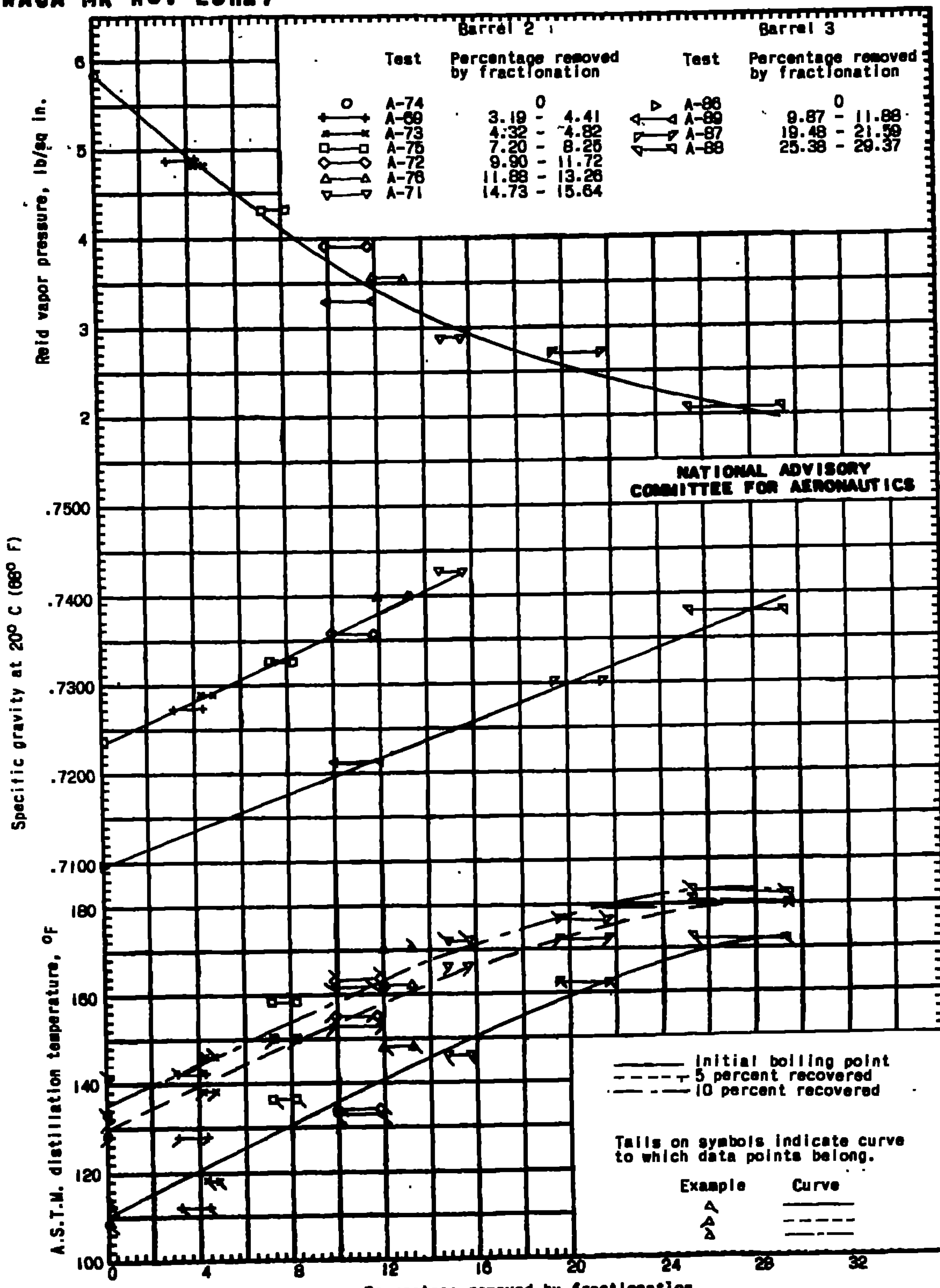


Figure 4. - Variation of several physical properties of the fuel samples with percentage removed by fractionation.

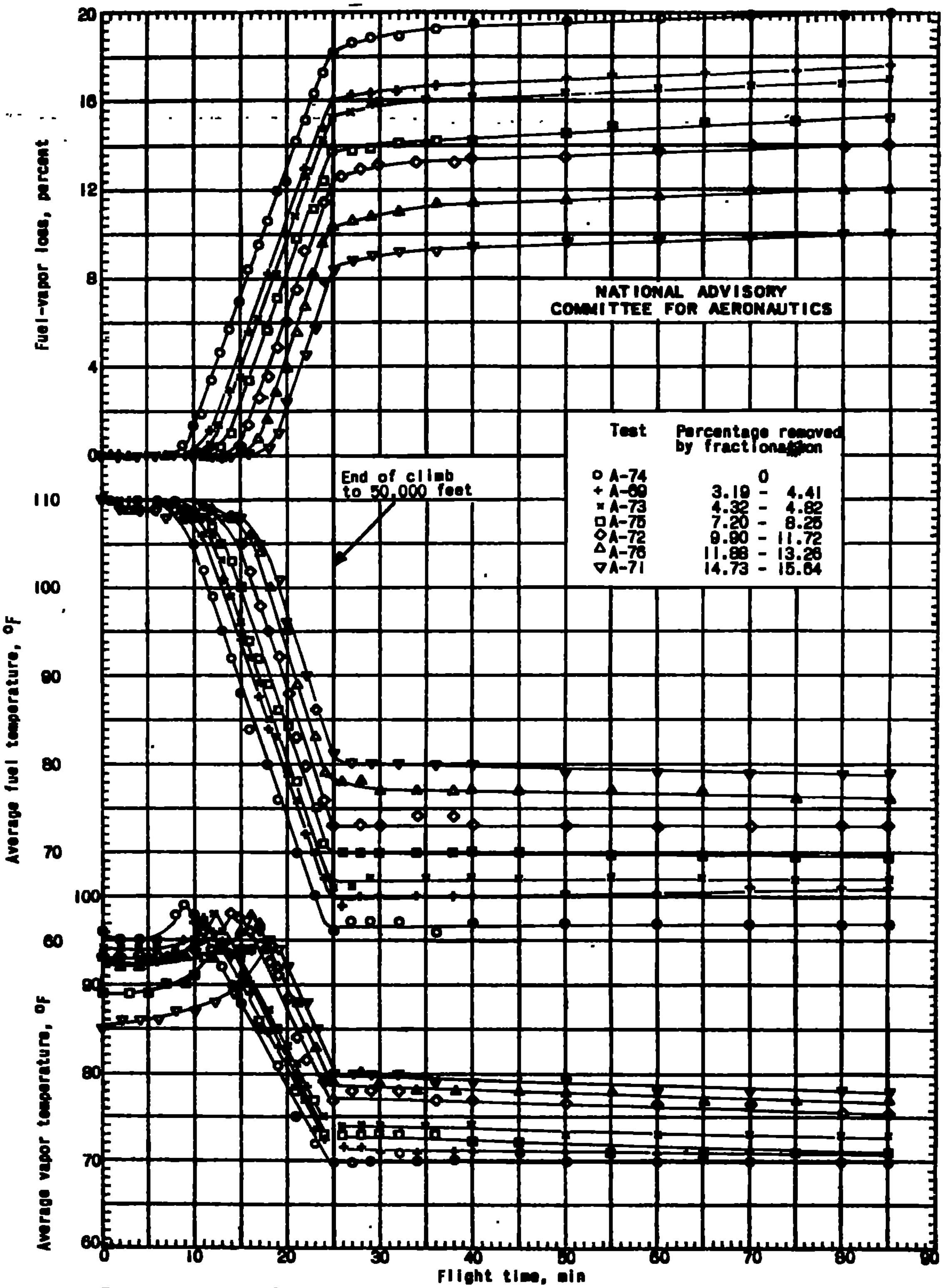


Figure 5. - Variation in fuel-vapor loss, fuel temperature, and vapor temperature while subjecting the fuel samples to simulated flight. Rate of climb, 2000 feet per minute to an altitude of 50,000 feet with level flight at this altitude to end of test.

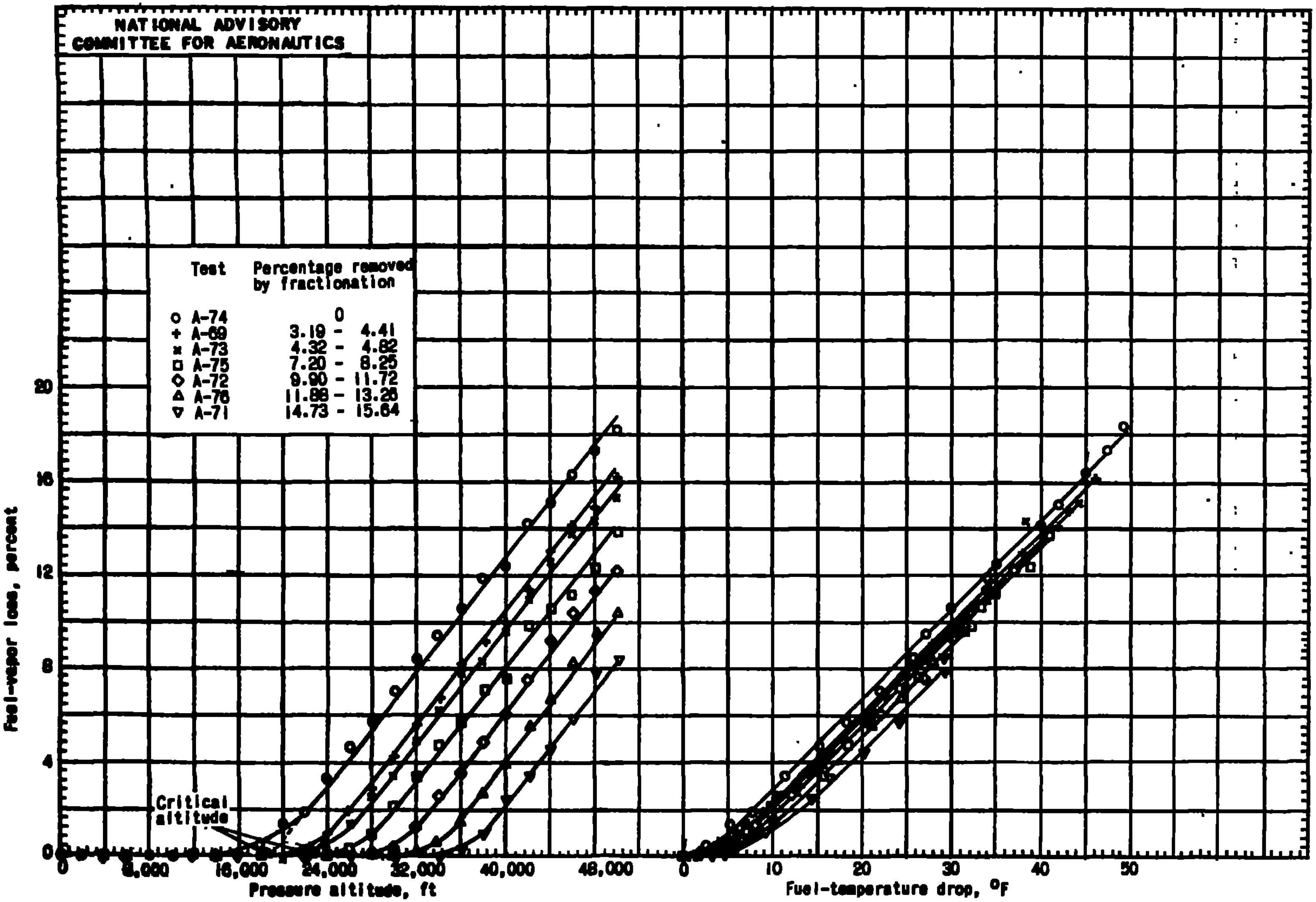


Figure 8. - Fuel-vapor loss plotted as a function of pressure altitude and drop in fuel temperature during simulated climb to an altitude of 50,000 feet.

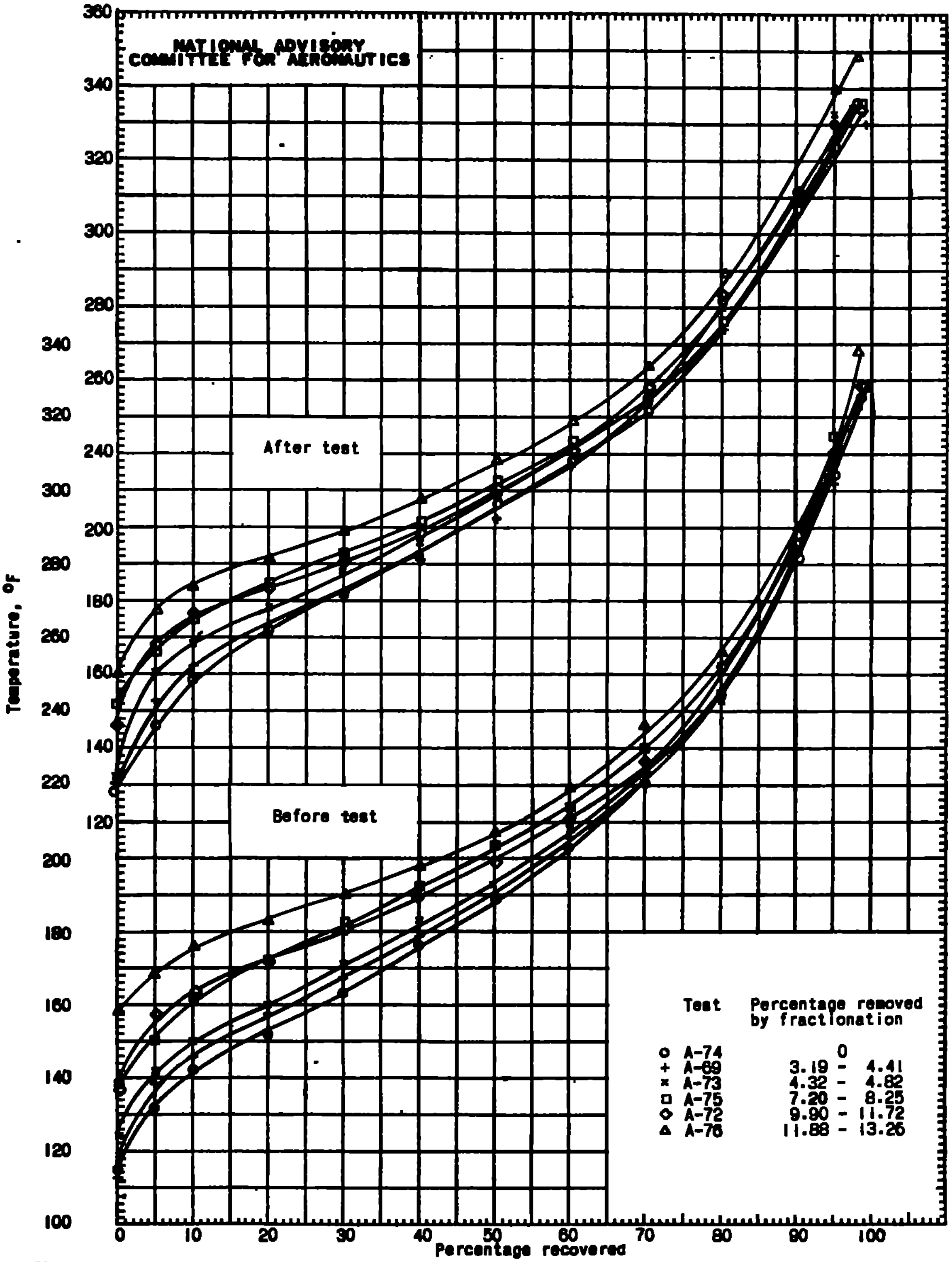


Figure 7. - A.S.T.M. distillation curves of some of the fuel samples before and after simulated flight.

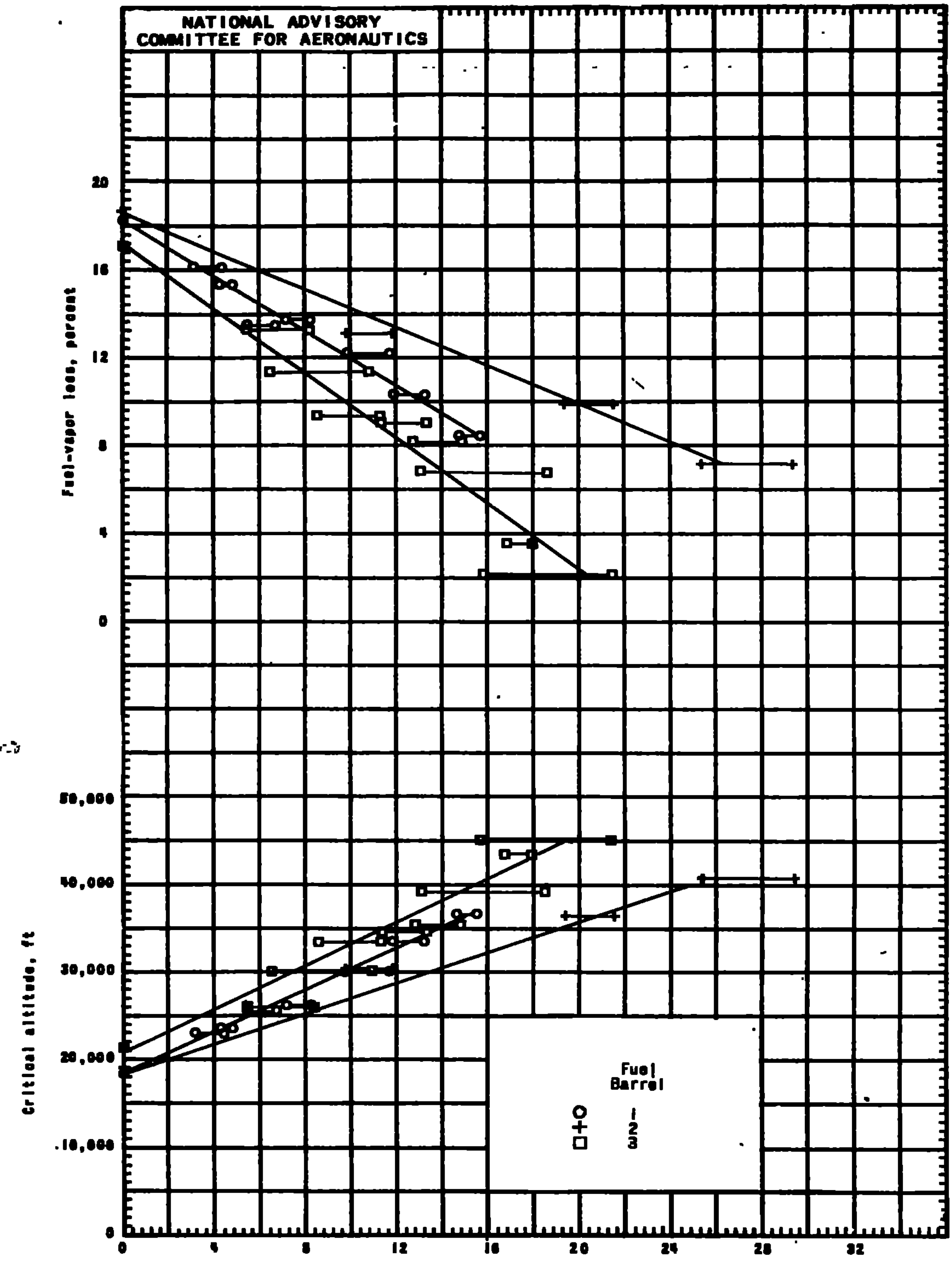


Figure 8. - Fuel-vapor loss during climb to 50,000 feet altitude and critical altitude as affected by amount of lower-boiling-point components removed from AN-F-28, Amendment 2, fuel.

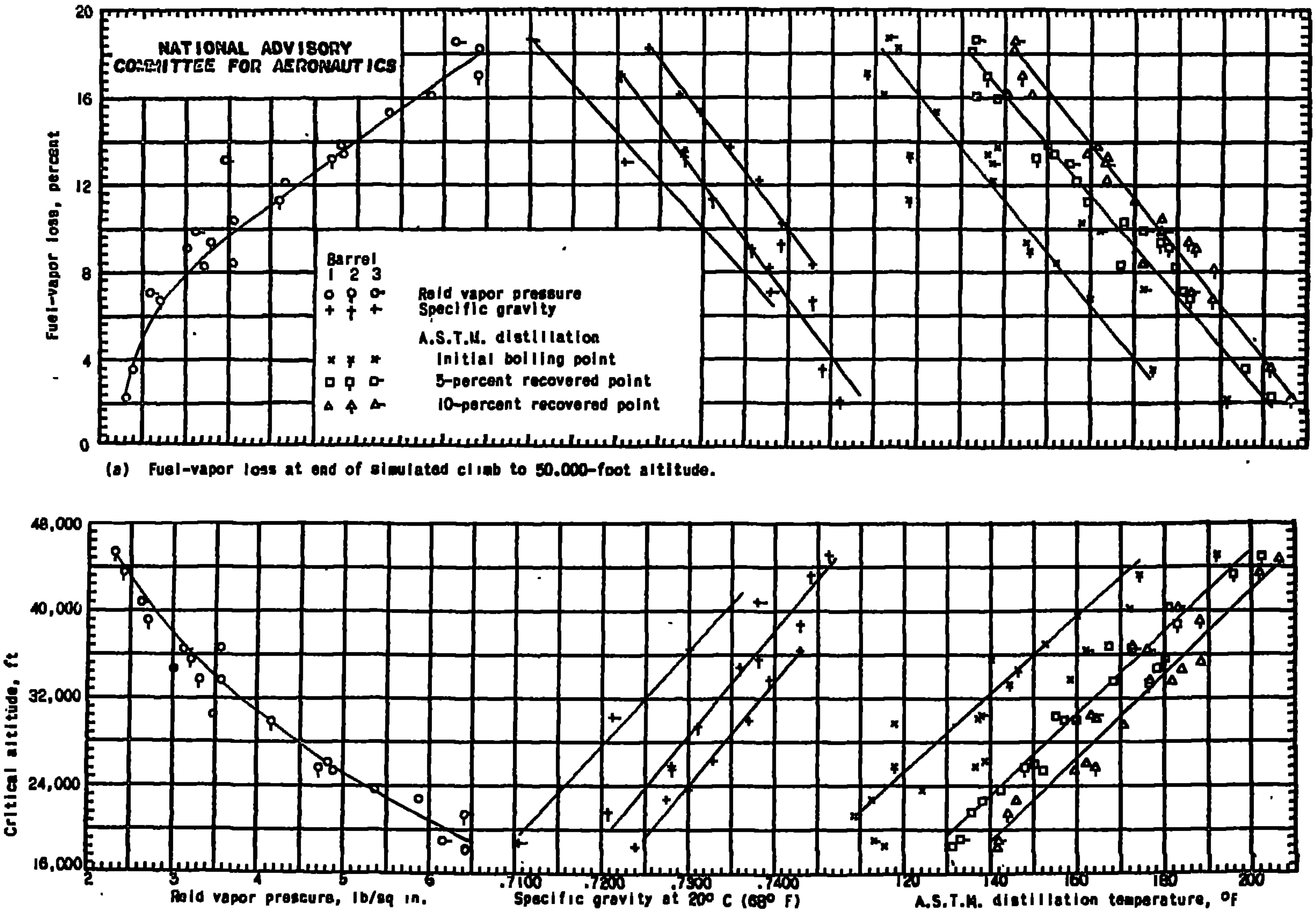


Figure 9. - The effect on fuel-vapor-loss characteristics of variation in some of the physical properties of the fuel. Fuel temperature at start of simulated flight, 110° F.